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A New Technique to Measure the Spectral Properties of Conifer Needles

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Careful measurements of the spectral properties of individual leaves are required to understand interactions of radiation with vegetation and to use effectively the data from future sensors with increasingly finer spectral resolution. Instruments capable of measuring the optical properties of leaves typically have integrating spheres with sample ports at least 10 mm in diameter. However, the leaves of many grasses and conifers are too small to cover completely the sample port. We describe a technique that enables the measurement of reflectance and transmittance of narrow leaves or needles with spectroradiometers equipped with a light source and integrating sphere. Measurement procedures and formulae for optical property calculations are presented. A test of the techniques resulted in absolute reflectance differences of 3% or less when comparing optical properties measured for whole leaves and narrow strips cut from the leaves. Thus, these techniques can accurately estimate the spectral properties of small leaves.

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INTRODUCTION

Evidence from geological research strongly indicates that direct identification of minerals through analysis of high spectral resolution images is possible. There are also indications that high spectral resolution remotely sensed data will enhance our ability to map vegetation species and to assess the physiological condition of vegetation (e.g., Vanderbilt, 1985; Milton et al., 1986).

Airborne and spaceborne remote sensing instruments are being developed with increasingly finer spectral resolution. For example, these fine spectral resolution data may be useful for detection of symptoms of forest decline (Rock et al., 1986; Teillet et al., 1985). Careful measurements of the reflectance and transmittance of conifer needles in the laboratory or field are required to

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document the changes in optical properties caused by stress.

Instruments capable of measuring the optical properties of leaves typically have integrating spheres with sample ports at least 10 mm in diameter. For example, the diameter of the sample port of the integrating sphere of the LI-COR LI-1800 spectroradiometer is 14.5 mm with an illumination beam diameter of 11.4 mm. These dimensions are well suited for leaves of many species which are larger than 15 mm. However, the narrow leaves of many grasses and the needles of conifers are too small to completely cover the sample port.

Simply reducing the sample port diameter will not suffice unless the beam illuminating the sample is also reduced. Restricting both sample port size and illumination beam width to the dimensions of a spruce needle (10–20 mm long and 1–2 mm wide), for example, may significantly degrade the spectral sensitivity of the spectroradiometer, especially for wavelengths where absorption is high and reflectance and transmittance are low.

Thus, alternative strategies are needed to measure the spectral properties of conifer needles. One alternative approach frequently used is to make a "solid" mat of needles by laying needles side by side (Daughtry and Biehl, 1984). This mat of needles is then placed over the sample port, and its spectral properties are measured. This technique has several problems. First, it is difficult to arrange conifer needles in a single layer with no gaps between needles. A few gaps may be acceptable for reflectance measurements but certainly not for transmittance measurements. Even one small gap between the needles may allow much more radiation into the integrating sphere than the rest of the sample, especially in the region of the spectrum where transmittance is low. Making the mat of needles several layers thick only confounds measurements of reflectance due to multiple scattering by the additional layers, and it also prohibits measurements of transmittance.

A second alternative approach for conifer needles is to consider the twig and its needles as the basic element of the canopy and to measure the spectral properties of the entire ensemble. However, to our knowledge, no spectroradiometer and integrating sphere in production has the depth of field and size required to accommodate such an ensemble of needles. Williams and Wood (1987) have developed a hemispherical illumination system for acquiring reflectance measurements of conifer shoots or branches, but their technique is not designed to acquire transmittance measurements.

Our objectives were 1) to determine a theoretical basis for measuring the optical properties of conifer needles and 2) to test the algorithm and procedures using simulated and real needles. We present three cases with equations for calculating reflectance and transmittance of leaves. Although the equations were developed for the LI-COR LI-1800 spectroradiometer and integrating sphere, the concepts are applicable to other spectroradiometers.

OPTICAL PROPERTY MEASUREMENTS

The principle involved with measuring the spectral properties of narrow leaves is that reflectance and transmittance of the leaves can be inferred from spectral measurements of a composite "scene" consisting of leaves and the background material between the leaves. Our discussion considers measurements for three cases: 1) leaves large enough to cover the entire sample port of the integrating sphere; 2) leaves too narrow to cover the sample port, but long enough to span the port; and 3) leaves too narrow and too short to span the sample port of the sphere, which necessitates supporting the leaves on "transparent" tape.

Case 1

In the first case, we review the standard calculation of reflectance and transmittance when the leaf covers the entire sample port.

For leaves and other nonhomogeneous materials a separate reference scan for reflectance and transmittance is required, particularly if absorptance is computed (absorptance = 1 − reflectance − transmittance). It is important that the same side of the sample be measured for reflectance and transmittance. The side that is illuminated (i.e., facing the inside of the sphere) for reflectance and reference (F_{wr}) measurements must also be illuminated (i.e., facing away from the sphere) for the transmittance measurement and its reference (F_{wt}). Additionally, a measurement of stray light (F_n) is required. To measure stray light, the sphere is configured in reflectance mode, but with no sample, and several scans are taken. Values for stray light should be very small, generally less than 0.005 of reference values across all wavelengths.

$$\text{reflectance} = \rho_s = \frac{(F_r - F_n)}{(F_{wr} - F_n)} \frac{\rho_r}{G_3}, \quad (1)$$

$$\text{transmittance} = \tau_s = \frac{F_t}{(F_{wt} - F_n)} \frac{\rho_r}{G_3}, \quad (2)$$

where

F_r = flux measured in reflectance mode,
F_t = flux measured in transmittance mode,
F_n = flux measured in reflectance mode with no sample,
F_{wr}, F_{wt} = flux measured in reference mode, for side of leaf illuminated during reflectance and transmittance measurements, respectively,
ρ_r = reflectance of $BaSO_4$ reference surface,
G_3 = function of sphere reflectance and geometry and sample reflectance.

Values of G_3 for the LI-1800 integrating sphere range from 1.000 to 1.008 and are assumed to be 1.000 for the calculations. See the Appendix for further description of this function.

Case 2

The second case deals with conifer needles that are longer than the diameter of the sample port of the integrating sphere. For example, needles of many of the pines exceed 50 mm in length. In this case, the needles may be laid side by side approximately a needle-width apart. The ends of the needles may be taped together for easier handling.

$$\rho_s = \frac{(F_r - F_n)}{(F_{wr} - F_n)} \frac{\rho_r}{(1 - f_6)} \frac{1}{G_2}, \quad (3)$$

$$\tau_s = \left[\frac{F_t}{(F_{wt} - F_n)} \rho_r - (\rho_w f_6 H_2)\right] \frac{1}{(1 - f_6)} \frac{1}{G_2}, \quad (4)$$

$$f_6 = \left[\frac{F_t}{(F_{wt} - F_n)} \rho_r - (G_2 \tau_s)\right] \frac{1}{(\rho_w H_2) - (G_2 \tau_s)} \quad (5)$$

where

ρ_w = reflectance of sphere wall,
f_6 = portion of the beam area that does not strike the sample,
G_2, H_2 = functions of sphere reflectance and geometry, sample reflectance and the portion of the beam area that does not strike the sample, f_6.
Values of G_2 and H_2 for the LI-1800 range between 1.000 and 1.008 and are assumed to be 1.000 in the calculations. See the Appendix for further description of these functions.

The key concept is that the area of the illumination beam that does not strike the sample (i.e., the needles), f_6, can be calculated and used to correct the reflected and transmitted fluxes. To calculate the area f_6, two series of measurements are required. First, flux transmitted through the array of needles (F_t), as well as the reference flux (F_{wt}), are measured as described above. Then, the sample is removed from the sample port of the integrating sphere and the needles are coated with an opaque flat black paint (e.g., Krylon #1602 ultra-flat black paint). Measurements of F_t and F_{wt} are repeated for the blackened needles. The area f_6 is calculated as the ratio of flux at 680 nm transmitted through the blackened sample (i.e., no radiation transmitted through the needles themselves) to the flux at 680 nm transmitted through the sample port with no sample in place. This wavelength was chosen because green leaves typically have minimum transmittance at 680 nm (e.g., Fig. 2).

Case 3

The third case extends the concepts presented in Case 2 and deals with conifer needles that are shorter than the diameter of the sample port of the integrating sphere. For example, needles of black spruce [*Picea mariana* (Mill.)] typically are only 6–12 mm long. In this case, the needles were removed from the twig and carefully arranged on a specularly transmitting background, i.e., Scotch brand magic transparent tape no. 810. Ideally the background would have 0% reflectance and 100% transmittance, i.e., clean dry air. However, because the tape is not an ideal background, the reflectance and transmittance of both sides of the tape must be measured also (using Case 1 equations):

$$\rho_s = \left[\frac{(F_r - F_n)}{(F_{wr} - F_n)} \rho_r \frac{1}{G_1} - f_{6b}\rho_b \right] \times \frac{1}{(1 - f_{6b})} - (\tau_s^2 \rho_b), \quad (6)$$

$$\tau_s = \left[\frac{F_t}{(F_{wt} - F_n)} \frac{\rho_r}{\tau_b} - \rho_w f_{6b} H_1 \right] \frac{1}{(1 - f_{6b})} \frac{1}{G_1}, \quad (7)$$

$$f_{6b} = \left[\frac{F_t}{(F_{wt} - F_n)} \frac{\rho_r}{\tau_b} - G_1\tau_s \right] \frac{1}{(\rho_w H_1) - (G_1\tau_s)}, \quad (8)$$

where

ρ_b = reflectance of the background (i.e., tape),
τ_b = transmittance of the background,
f_{6b} = portion of the illumination beam that does not strike the sample that is mounted on a specularly transmitting background,
G_1, H_1 = functions of the sphere reflectance and geometry, sample reflectance, background reflectance, and the portion of the beam that does not strike the sample.

MEASUREMENT PROCEDURE

Figure 1 diagrammatically describes the arrangement of the LI-1800 integrating sphere. Measurements are taken by placing the illuminator in the reference port and taking a reference scan [Fig. 1a]. The reference material and the material coating the sphere walls is barium sulfate ($BaSO_4$), the reflectance properties of which can be compared with a known standard. After a reference scan, the

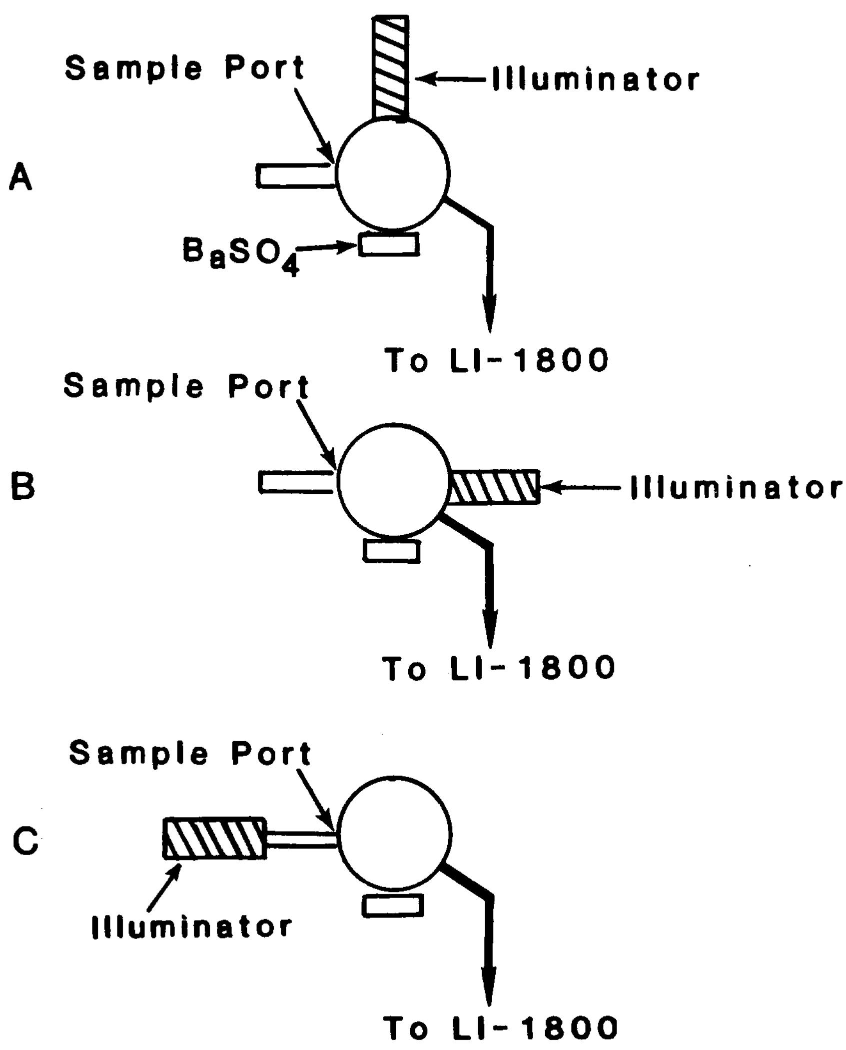


Figure 1. The integrating sphere of the LI-1800 configured in A) the reference mode, B) the reflectance mode, and C) the transmittance mode. Measurements are taken by placing the illuminator in the reference port and taking a reference scan. The reference material and the material coating the walls is barium sulfate ($BaSO_4$). After a reference scan, the illuminator is moved to the reflectance or transmittance port in order for the beam to strike or pass through the sample, respectively.

illuminator is moved to the reflectance [Fig. 1b] or transmittance [Fig. 1c] port in order for the beam to strike or pass through the sample, respectively.

The following procedures are recommended for measuring the optical properties of conifer needles:

1. Determine sphere wall reflectance by making a measurement in transmittance mode with no sample (F_{tn}) and a measurement in reference mode with no sample (F_{wn}). Sphere wall reflectance (ρ_w) is calculated by

$$\rho_w = \frac{F_{tn}}{(F_{wn} - F_n)} \rho_r. \qquad (9)$$

2. Measure reflectance and transmittance of tape with adhesive side toward the illumination source. Calculate tape reflectance (ρ_b) with Eq. (1) and transmittance (τ_b) with Eq. (10).

$$\tau_b = \frac{F_t}{(F_{wt} - F_n)} \frac{\rho_r}{\rho_w} \frac{1}{H_1} \qquad (10)$$

3. Detach needles from twig and place on tape with approximately 1 needle width between needles. When needles were placed closer than 1 needle width, we observed that reflectance increased slightly apparently due to multiple reflections from adjacent needles.
4. Select a sample holder that is approximately one-half as thick as the needles and carefully position the sample holder with needles in place in the sample port of the integrating sphere such that the needles are toward the sphere.
5. Measure spectral response in reference mode [Fig. 1a] and in reflectance mode [Fig. 1b].
6. Mark the sample holder so that it can be repositioned accurately in the sample port (see step 7 for rationale). Rotate sample holder so that needles are away from the sphere and are toward the illumination beam for the transmittance mode. Measure spectral response in reference mode [Fig. 1a] and in transmittance mode [Fig. 1c].
7. Paint the surface of the needles which is not on the tape with an opaque flat black paint, carefully reposition the sample holder in the sample port, and remeasure spectral response in transmittance mode. (Note: Do not remove the needles from the tape, or the tape from the sample holder, to paint them. It is imperative that the painted sample be repositioned in the sample port precisely as it was in step 4. All calculations assume that the sample area illuminated is unchanged for all spectral measurements of a sample.)
8. Compute f_6 or f_{6b} for Eq. (5) or Eq. (8), respectively, at 680 nm using the measured transmittance of the blackened array of needles. This assumes that the transmittance of the blackened needles themselves at 680 nm is 0.0.
9. Input f_6 or f_{6b} into Eq. (4) or Eq. (7), respectively, to determine the actual transmittance of the unpainted conifer needles at 680 nm.

The calculated value for transmittance at 680 nm is then used in Eq. (5) or Eq. (8) to determine f_6 or f_{6b} for all normal (unpainted) needle reflectance [Eq. (3) or Eq. (6)] and transmittance [Eq. (4) or Eq. (7)] calculations. It is not necessary to paint every sample of needles if one assumes that transmittance at 680 nm does not differ significantly among the samples.

RESULTS AND DISCUSSION

As a test of the algorithms and procedures outlined above, reflectance and transmittance of squares of green Nextal suede coated paper that completely covered the sample port of the integrating sphere were measured (Case 1). The squares of paper were cut into narrow strips (1–2 mm wide) and the spectral properties were remeasured without a tape background (Case 2) and with a tape background (Case 3). The results for Cases 2 and 3 were within 4% of the values for Case 1. Some of the differences observed were probably due to the exposed cut edges of the paper which were gray, not green.

An additional test of the procedures outlined above was conducted using leaves of southern magnolia (*Magnolia grandiflora* L.). Southern magnolia leaves were nearly ideal for this purpose since they are large (50–80 mm wide) and leathery and their optical properties did not change appreciably during the measurement period of 10 min per sample. The best results achieved showed average reflectance for Case 2 varied by less than 3% of value from the Case 1 average over the 400–1100 nm wavelength range, while transmittance varied

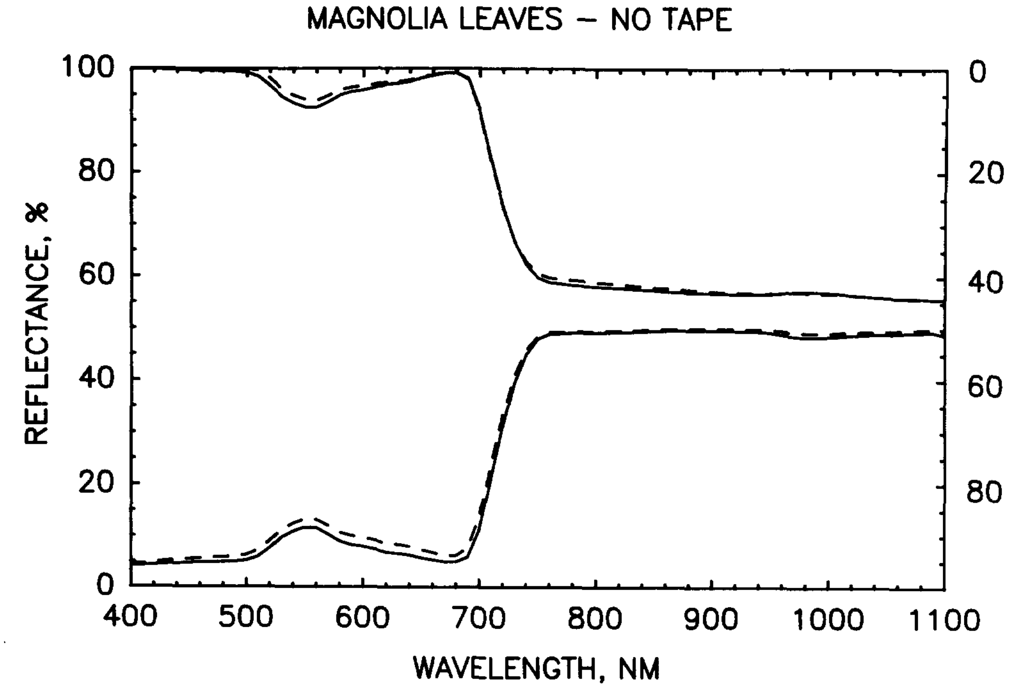
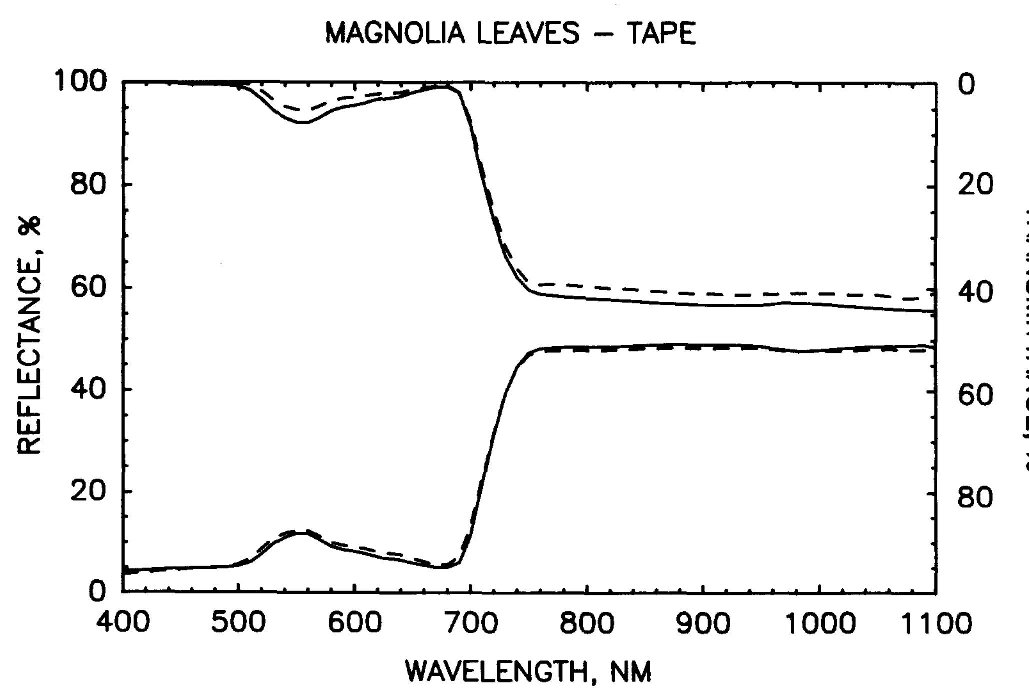


Figure 2. Comparison of reflectance and transmittance spectra of whole southern magnolia leaves (Case 1) (—) and strips of leaves (Case 2) (---).

Figure 3. Comparison of reflectance and transmittance spectra of whole southern magnolia leaves (Case 1) (—) and strips of leaves mounted on transparent tape (Case 3) (---).



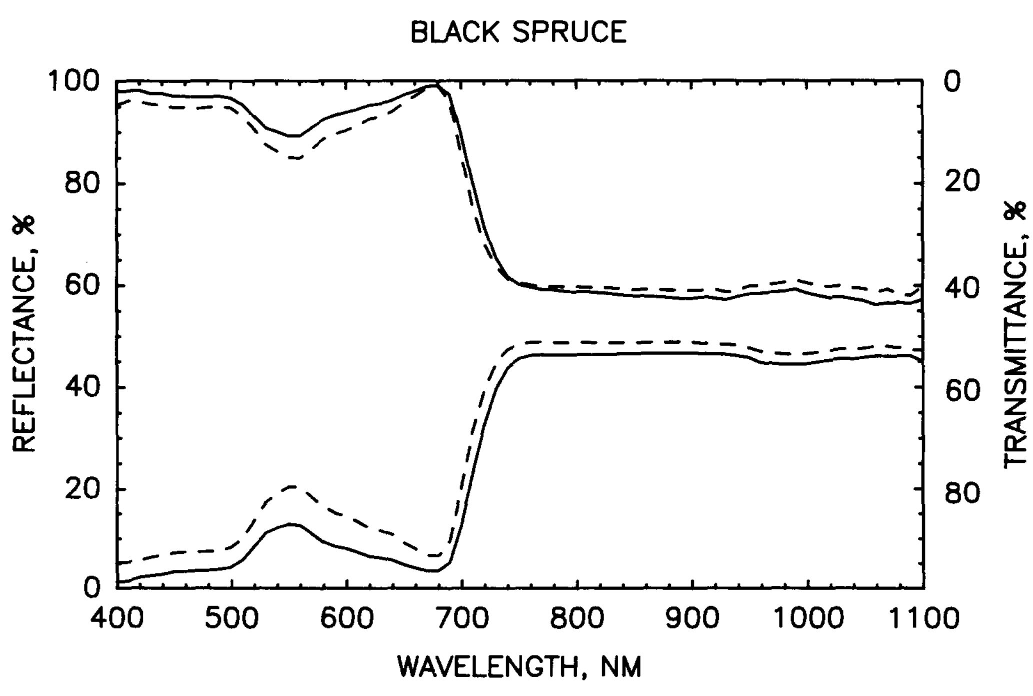
by 2% or less (Fig. 2). Comparisons of the spectral properties of whole leaves (Case 1) and strips of leaves (Case 3) showed maximum differences of about 3% for reflectance and transmittance across the spectrum (Fig. 3). Typically average reflectance and transmittance differences between Cases 1 and 2 were on the order of 4% and 6%, respectively. Differences between Cases 1 and 2 tended to be 7% or less across the spectrum. In general, the results for Cases 2 and 3 were slightly higher for reflectance and slightly lower for transmittance than whole leaf measurements.

These procedures were also tested with five sets of three, seven, and 11 black spruce needles from the same branch. Overall, the coefficients of variation (CV) were less than 8%. When either seven or 11 needles per set were measured, the CV was less than 5%. This suggests that using a greater number of needles and intercepting a larger portion of the illumination beam may improve the reliability of the measurements. Even with seven needles per set the needles appeared to intercept less than 50% of the illumination beam. As more needles were placed in the illumination beam, the calculated reflectance values increased slightly, presumably due to reflective interactions between adjacent needles. Nevertheless, the relatively small CV further indicates that the procedures outlined here can produce repeatable and reliable results. Figure 4 illustrates typical reflectance and transmittance spectra of black spruce needles acquired using the techniques outlined for Case 3.

CONCLUSIONS

The techniques described here provide reasonable and repeatable measurements of the reflectances and transmittances of narrow leaves and needles. The procedures require careful handling of the samples and attention to detail in making measurements. Particular attention must be paid to 1) the tedious task of blackening the needles and 2) the alignment of the sample holder for the measurements of the blackened needles. We found that using artist paint brushes (sizes 00 and 000) and a quick drying ultra-flat black paint (e.g., Krylon 1602) facilitated blackening of the needles. Misalignment errors were reduced, and the repeatability of our measurements was improved by mounting the array of needles on a sample holder that could be precisely repositioned over the sample port. The sample holder was a small square of aluminum about 0.5 needle thick (0.7 mm) with a

Figure 4. Typical reflectance and transmittance spectra for black spruce needles measured using Case 3 procedures: (—) previous year; (---) current year.



22 mm diameter hole. The array of needles was taped in the center of the hole, and the sample holder with the needles was placed over the sample port of the integrating sphere. Marks on the sample holder and integrating sphere were used for alignment.

Comparisons between measurements of whole samples and strips of green paper or leaves derived from whole samples suggest that the method provides repeatable and reliable estimates of transmittance and reflectance. Our tests show, however, an apparent systematic bias by slightly underestimating transmittance and slightly over estimating reflectance. We are currently considering alternative integrating sphere configurations for future studies.

APPENDIX

Definition of Variables

In this section we define variables and calculate their values for the LI-COR 1800-12 integrating sphere (LI-COR, 1983). The procedures are applicable to other integrating spheres as well.

Variables Related to Sphere (data from LI-COR, 1983):

A_t = total sphere area = 18,146 mm^2,
A_e = area of exit port = 32 mm^2,
A_i = area of entrance port = 169 mm^2,
A_s = area of sample port = 165 mm^2,
A_r = area of reference = 102 mm^2,
A = area of sphere coating = 17,678 mm^2,
A_b = area of illumination beam = 102 mm^2.

Properties of Sphere at 680 nm:

ρ_r = reflectance of reference surface = 0.980,
ρ = reflectance of sphere coating = 0.955.

Variables Related to Sample Surface:

ρ_s = reflectance of sample,
τ_s = transmittance of sample,
ρ_b = reflectance of background,
A_{b1} = area of sample which intercepts illumination beam,
A_{b0} = area of illumination beam *not* intercepted,
A_{s1} = area of sample port which is covered by sample surface,
A_{s0} = area of sample port which is *not* covered by sample.

Intermediate Functions:

$$f_0 = \frac{A\rho + A_s\rho_s}{A + A_s}, \qquad 0.946 < f_0 < 0.955,$$

$$f_1 = \frac{A\rho + A_r\rho_r + A_s\rho_s}{A + A_r + A_s}, \qquad 0.946 < f_1 < 0.956,$$

$$f_2 = \frac{A\rho + A_r\rho_r + A_{s1}\rho_s}{A + A_r + A_{s1}}, \qquad 0.946 < f_2 < 0.956,$$

$$f_3 = \frac{A\rho + A_r\rho_r}{A + A_r} = 0.955,$$

$$f_4 = \frac{A\rho + A_{s1}\rho_s}{A + A_{s1} + A_{s0}}, \qquad 0.946 < f_4 < 0.959,$$

$$f_5 = \frac{A_e + A_i}{A_t} = 0.011,$$

$$f_6 = \frac{A_{b0}}{(A_{b1} + A_{b0})}, \qquad 0.0 < f_6 < 1.0,$$

$$f_7 = \frac{A\rho + A_r\rho_r + A_{s1}\rho_s + A_{s0}\rho_b}{A + A_r + A_{s1} + A_{s0}}, \qquad 0.946 < f_7 < 0.956,$$

$$f_9 = \frac{A\rho + A_{s1}\rho_s + A_{s0}\rho_b}{A + A_{s1} + A_{s0}}, \qquad 0.946 < f_9 < 0.955.$$

Note that several of the above functions are special cases of others. These functions may be grouped into the three cases from the ideal to the most general.

Case 1. Sample is not on a background and covers the sample port. Functions: f_3, f_5, f_1, and f_0.

Case 2. Sample is not on a background and does not cover the sample port. Functions: f_3, f_5, f_2, and f_4.

Case 3. Sample is on a background and does not cover the sample port. Functions: f_3, f_5, f_7, and f_9.

Function f_7 reduces to f_2, which reduces to f_1 as one goes from the most general case to the "ideal" case. Function f_9 reduces to f_4, which reduces to f_0 as one goes from the most general to the ideal case.

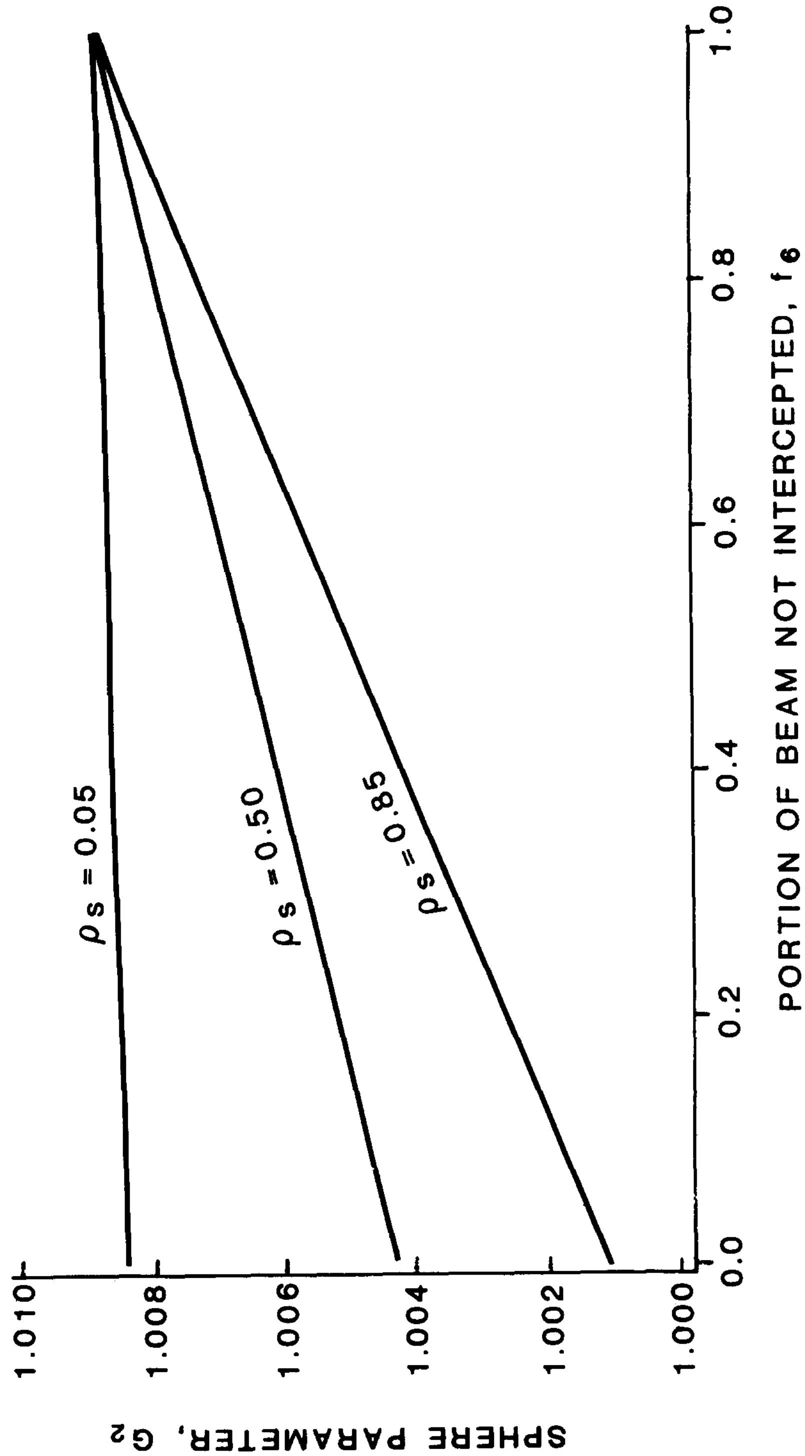


Figure 5. Changes in G_2 as a function of the area of the sample port not covered by the sample (f_6) for three values of sample reflectance.

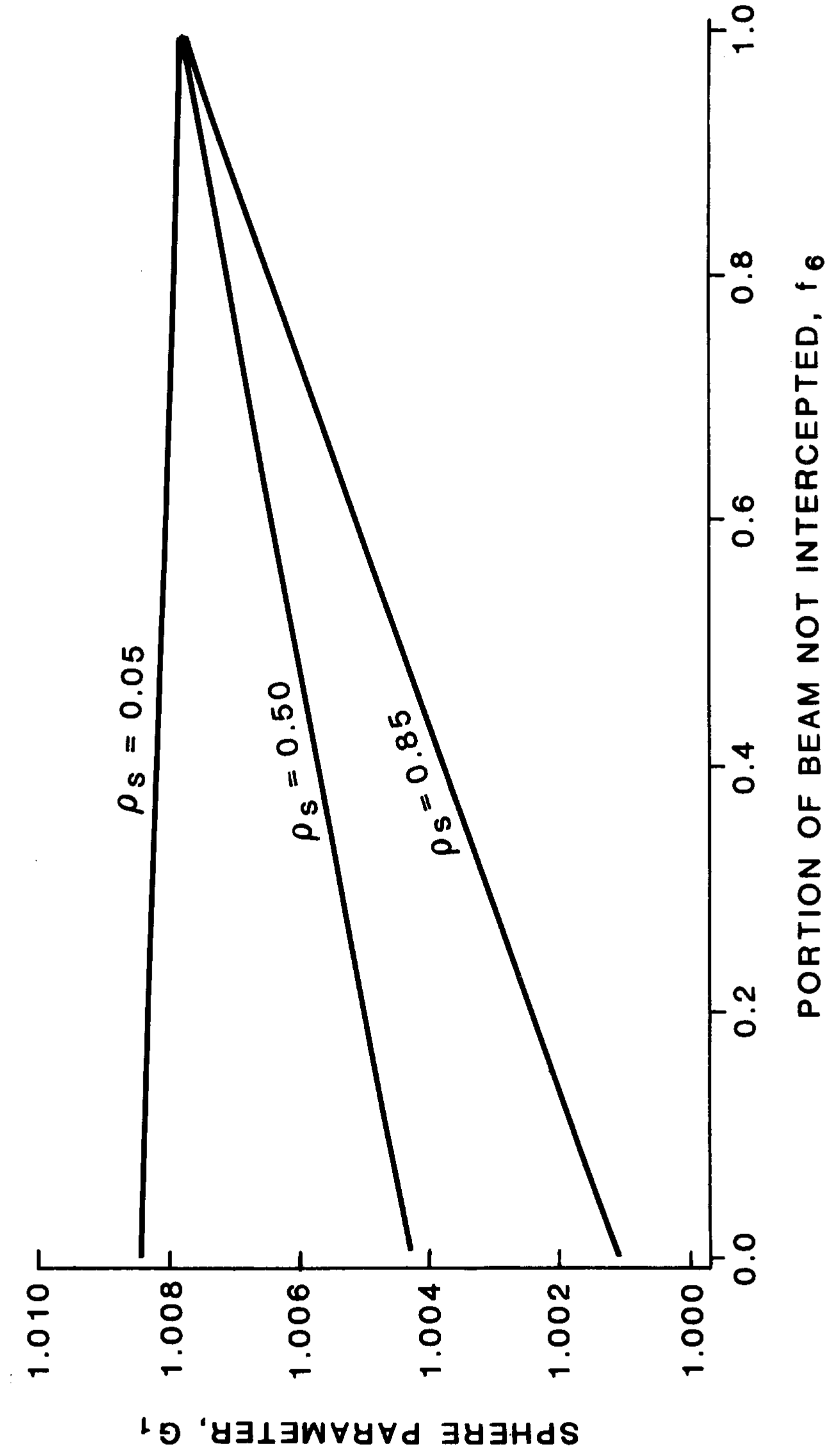


Figure 6. Changes in G_1 as a function of the area of the sample port not covered by the sample (f_6) for three values of sample reflectance.

Sphere Parameters:

The following two parameters are for the most general case where the sample is on a background and only covers a portion of the sample port (i.e., Case 3).

$$G_1 = \frac{1 + f_3(1-f_5)[1-f_2(1-f_1)]^{-1}}{1 + f_9(1-f_5)[1-f_7(1-f_5)]^{-1}},$$

$$H_1 = \frac{[1-f_2(1-f_1)]^{-1}}{1 + f_9(1-f_5)[1-f_7(1-f_5)]^{-1}}.$$

The following two parameters are for the case where the sample is not on a background and only covers a portion of the sample port (i.e., Case 2). Note that G_2 and H_2 are special case of G_1 and H_1, respectively.

$$G_2 = \frac{1 + f_3(1-f_5)[1-f_2(1-f_5)]^{-1}}{1 + f_4(1-f_5)[1-f_2(1-f_5)]^{-1}},$$

$$H_2 = \frac{[1-f_2(1-f_5)]^{-1}}{1 + f_4(1-f_5)[1-f_2(1-f_5)]^{-1}}.$$

The following parameter is for Case 1 where the sample is not on a background and covers the entire sample port. Note that G_3 is a special case of G_1 (and G_2):

$$G_3 = \frac{1 + f_3(1-f_5)[1-f_1(1-f_5)]^{-1}}{1 + f_0(1-f_5)[1-f_1(1-f_5)]^{-1}}.$$

EVALUATION OF SPHERE PARAMETERS

The sphere parameters G_1, G_2, G_3, H_1, and H_2 are functions of the proportion of the sample port that is not covered by the sample (f_6), the reflectance of the sample (ρ_s), and the reflectance of the background (ρ_b), if present. In Eqs. (1) and (2) for a sample covering the entire sample port the factor G_3 linearly decreases from 1.0089 when ρ_s is low (0.00) to 1.00002 when ρ_s is high (1.00). When the sample does not cover the entire sample port, Figures 5 and 6 illustrate the changes in G_2 and G_1, respectively, as a function of f_6 for three values of sample reflectance (ρ_s). When reflectance of the sample is high ($\rho_s = 0.85$), then both G_2 and G_1 change from 1.001 to 1.008 as f_6 increases from 0.0 (sample port completely covered) to 1.0 (no sample). When the sample reflectance is low ($\rho_s = 0.05$), both G_2 and G_1 are essentially constant and are independent of f_6.

The factor, H_2, in Eq. (4) ranges from 1.0001 to 1.0002 as f_6 increases from 0.0 to 1.0 for a sample with low reflectance ($\rho_s = 0.05$). When ρ_s is high (0.85), H_2 is 1.0001 and is independent of f_6.

For biological materials which have some inherent variability in their optical properties, the values for G_1, G_2, G_3, H_1, and H_2 can be assumed to be 1.000 without significantly affecting the accuracy of the calculations.

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